

Discovery of a new group of double-periodic RR Lyrae stars in the OGLE-IV photometry

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ABSTRACT

We report the discovery of a new group of double-periodic RR Lyrae stars from the analysis of the OGLE-IV Galactic bulge photometry. In 11 stars identified in the OGLE catalog as first overtone pulsators (RRc stars) we detect additional longer period variability of low amplitude, in the mmag regime. One additional star of the same type is identified in a published analysis of the *Kepler* space photometry. The period ratio between the shorter first overtone period and a new, longer period lies in a narrow range around 0.686. Thus, the additional period is longer than the expected period of the undetected radial fundamental mode. The obvious conclusion that addition periodicity corresponds to a gravity or a mixed mode faces difficulties, however.

Key words: stars: horizontal branch – stars: oscillations – stars: variable: RR Lyrae

1 INTRODUCTION

RR Lyrae stars are classical pulsators of great astrophysical importance. They serve as excellent distance indicators and tracers of the old stellar populations, enabling galactic structure, kinematics and evolution studies. Majority of these stars are radial, single-periodic pulsators, pulsating either in the fundamental mode (F-mode, RRab stars) or in the first overtone (1O-mode, RRc stars). Double-mode pulsators pulsating simultaneously in the fundamental and in the first overtone modes (RRd stars) are also known and numerous. In the Petersen diagram, i.e. a diagram of shorter-to-longer period ratio vs. the longer period these stars form a well defined group with characteristic period ratio in a range 0.725 – 0.747 (depending on the period; open circles in Fig. 1, Soszyński et al. 2014). In all groups the Blazhko effect, quasi-periodic modulation of pulsation amplitude and phase is observed (for a review see Szabó 2014). The effect is more frequent in RRab stars than in RRc stars. Only recently the effect was discovered in RRd stars (Soszyński et al. 2014; Jurcsik et al. 2014; Smolec et al. 2015). RRc stars are prone to fast and irregular period changes on a time-scales shorter than predicted from stellar evolution theory (e.g. Catelan & Smith 2015).

Recently, new groups of double-periodic RR Lyrae stars were identified, thanks to precise and nearly continuous pho-

tometry of the space missions, *CoRoT* and *Kepler*. The discoveries include fundamental plus second overtone radial mode pulsators [e.g. Benkő et al. (2010), for a review see Moskalik (2014); diamonds in Fig. 1] and mysterious group of double-mode radial-non-radial pulsators. In this group we observe the dominant pulsation in the first overtone mode and additional variability with a shorter period. In the Petersen diagram (triangles in Fig. 1), these stars seem to form two groups with period ratios clustering around ≈ 0.61 and ≈ 0.63 . Space photometry (Szabó et al. 2014; Moskalik et al. 2015; Molnár et al. 2015) indicates that this form of pulsation must be common among RRc stars, as 13 out of 14 RRc stars observed from space show the phenomenon. Majority of the 0.61 stars plotted in Fig. 1 however, were detected only recently in the third phase of the Optical Gravitational Lensing Experiment (OGLE; see eg. Udalski et al. 2008) photometry of the Galactic bulge by Netzel, Smolec & Moskalik (2015). We also note that in RRc stars observed from space other low frequency signals were detected and interpreted as non-radial gravity modes (Moskalik et al. 2015).

In this Letter we describe the discovery of a new group of double-periodic pulsators among stars identified as RRc. In the analysis of a top-quality sample of OGLE-IV photometry of the Galactic bulge (Soszyński et al. 2014) we have found 11 stars that show yet another period ratio that cannot be explained with simultaneous excitation of two radial modes. These stars are marked with filled circles in Fig. 1. The additional periodicity is longer than the first overtone

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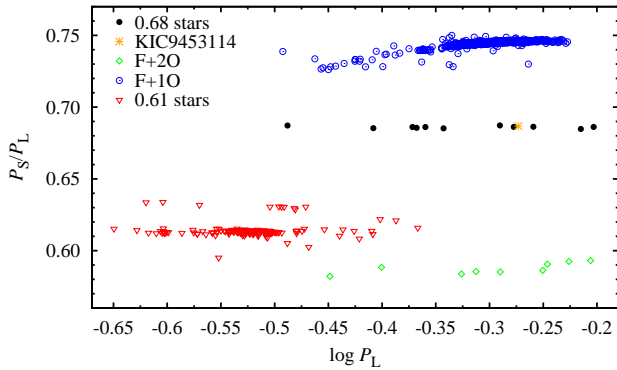


Figure 1. Petersen diagram for multiperiodic RR Lyrae stars. P_L and P_S are longer and shorter period, respectively, and correspond to different pulsation modes in the groups plotted in the diagram.

period and, as comparison with RRd stars clearly reveals, much longer than the expected period of the undetected radial fundamental mode. A literature search revealed yet another member of the group in the *Kepler* photometry of RRc stars (Moskalik et al. 2015). In the following sections we describe our analysis and summarize the properties of the new group. In Section 5 we briefly consider possible explanation for the group.

2 DATA AND ANALYSIS

Data used for analysis were collected during the fourth phase of the OGLE project. For some stars we used additionally data from the third phase. OGLE-IV collection of variable stars (Soszyński et al. 2014) contains 38 257 RR Lyrae stars, including 10 825 RRc stars and 174 RRd stars. Our goal is to search for additional, low amplitude signals in stars pulsating in the first overtone (RRc and RRd). Detecting weak signals requires possibly the lowest noise level, which is best met by stars with the largest number of observations. Hence, for our analysis we chose stars located in the most frequently observed fields, their numbers are 501 and 505 in OGLE-IV. For each star in these fields we have more than 8 000 datapoints. Altogether, there are 485 RRc and 4 RRd stars in these fields, which is also a reasonable number for manual analysis. We used observations in the *I*-band only (more numerous than the *V*-band data). In publicly available OGLE-IV data there are four observational seasons available. Length of the data is about 1334 d for most stars.

Data were analysed manually using standard consecutive prewhitening method. Discrete Fourier transform allows to find significant frequencies in the spectrum. We considered only those frequencies for which signal-to-noise ratio was $S/N \geq 4$. All detected frequencies were fitted to the data in the form:

$$m(t) = m_0 + \sum_{k=1}^N A_k \sin(2\pi\nu_k t + \phi_k), \quad (1)$$

where ν_k are frequencies, A_k and ϕ_k are amplitudes and phases. Only resolved frequencies are included in (1). We consider two frequencies unresolved if separation between them $\Delta\nu < 2/T$, where T is length of the data. When all

significant frequencies were included in the sum, we removed points deviating from the fit by more than 4σ .

In the data of many stars slow trend is present. It manifests in the frequency spectrum as a signal at low frequencies and gives rise to daily aliases at integer frequency values. We model the slow trends either with a long-period ($\approx 50\,000$ d) sine function or with low-order polynomial.

In many stars, after prewhitening with the frequency of the first overtone, ν_{1O} , and its harmonics, close peaks were detected at $k\nu_{1O}$, forming either equidistant triplets (multiplets) or close doublets. These are a signature of the Blazhko effect. We fitted these signals in the form $k\nu_{1O} \pm \Delta\nu$, where $\Delta\nu$ is a separation between main frequency and the side peaks.

In other stars, after prewhitening, unresolved signal remains at the location of ν_{1O} and/or its harmonics. It indicates that first overtone is not stationary, but its amplitude and/or phase change with time on a time scale comparable to or longer than the data length. Such signals increase the noise level in the transform and may hide the additional low amplitude signals, which we search for. To get rid of the non-stationary signals we used time-dependent prewhitening method proposed by Moskalik et al. (2015) (see Netzel, Smolec & Moskalik 2015, for application to OGLE data). Whenever possible, in order to investigate long-term variation of the first overtone, we combined OGLE-IV data with OGLE-III data (Soszyński et al. 2011), which, in some cases revealed a long-period Blazhko modulation. Irregular phase (period) changes of the first overtone are also very frequent.

3 RESULTS

As a result of our study we identified several interesting and well known phenomena: Blazhko effect, period-changing stars and double-periodic stars with additional non-radial, shorter period mode, with characteristic ≈ 0.61 period ratio to the first overtone period. These results will be described elsewhere (Netzel et al., in prep.). In addition, we found a group of 11 stars (2% of the sample) with additional low frequency signal. Corresponding period is longer than first overtone period; period ratios, P_{1O}/P_x fall within a narrow range from 0.6848 to 0.6872 with average value of 0.6860. Such period ratios were not reported in the literature before. Properties of the stars are summarized in Tab. 1.

A literature search revealed one additional RRc star observed by *Kepler* in which additional longer period was detected with period ratio falling in the same range (see f_5 in tab. 7 in Moskalik et al. 2015). Data for the star are in the last row of Tab. 1.

Stars with the additional frequency are plotted with filled circles on the Petersen diagram in Fig. 1. Star found in the *Kepler* photometry is marked with a different symbol and it fits the progression formed by the OGLE stars very well. All stars form a tight horizontal sequence below RRd stars. Fig. 2 shows only the newly found stars. No clear structure is visible within the group.

We note that period ratios of RRd stars cover a wide range in the Petersen diagram with period ratio clearly correlated with the period of the fundamental mode. The large range of period ratios of RRd stars corresponds to the large

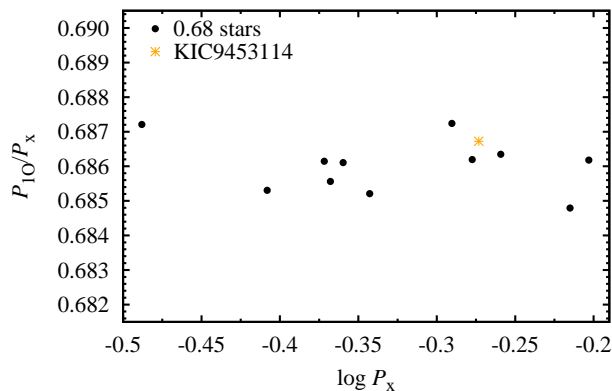


Figure 2. Petersen diagram for stars with additional frequency.

metallicity spread in the Galactic bulge, as model calculations indicate (eg. Soszyński et al. 2011). Without identification of the additional pulsation mode and appropriate pulsation models (see Sec. 5) we cannot infer about metallicities or relation between metallicity and location of the star in the Petersen diagram for the newly discovered group.

The analysed stars are located in the most dense stellar fields in the Galactic bulge, in which probability of blending is very high. The tight progression formed by a new group in the Petersen diagram and nearly constant period ratio with the first overtone period are a strong argument that the additional signal is real and intrinsic to the analysed RRc stars. Even more, in six stars we detect combination frequencies of the additional and first overtone frequencies which proves that the two signals originate from the same star. The form of the combination frequency is written in the penultimate column of Tab. 1. In three stars $S/N > 4$ for signal at combination frequency (marked with bold font). In other three stars we see a signal precisely at the position of combination frequency (within frequency resolution of the spectrum), but with $3 < S/N < 4$.

The unknown period is longer than the period of the unseen fundamental mode (see Fig. 1). This has an immediate consequence: if additional variability corresponds to pulsation mode, it can not be radial. Even more, it can not correspond to the purely acoustic mode, but must be a gravity mode or a mode of mixed character. As such explanation faces difficulties (Sec. 5) we analysed the light curves of the dominant pulsation mode to check whether the RRc identification in the OGLE catalog is correct. The light curves folded with the first overtone period are plotted in Fig. 3 sorted by the increasing period. Shapes are typical for RRc stars including the characteristic bump-feature preceding the maximum light. Period change, well visible for some longer period stars, is also characteristic for RRc stars. It also contributes to the larger photometric dispersion of some of the light curves. The other factor responsible for different dispersion of the light curves presented in Fig. 3 is difference in mean brightness of the stars: dispersion is larger for fainter stars.

Light curve shapes can be described quantitatively with the Fourier decomposition parameters, which display characteristic progression with the pulsation period, depending on the pulsation mode. In Fig. 4 we compare the Fourier decomposition parameters for our stars with parameters for

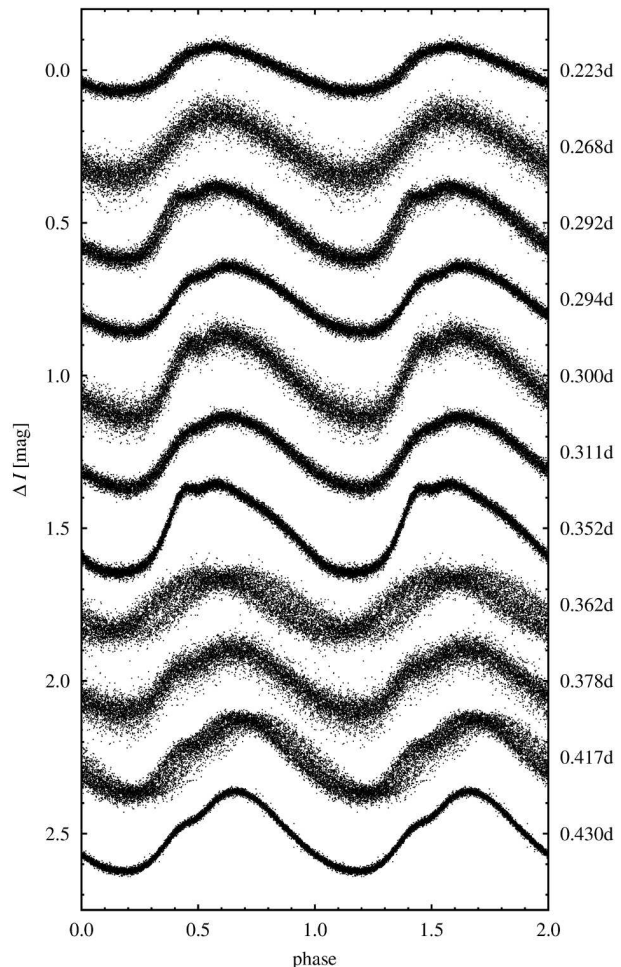


Figure 3. Light curves of stars with additional frequency phased with a period of the first overtone. They are ordered according to increasing period.

RRc stars from the Galactic bulge and OGLE-III catalog (Soszyński et al. 2011). Errors in determination of Fourier decomposition parameters for our stars are usually smaller than symbol size. Parameters for all 11 stars are within typical for RRc stars at given pulsation period. Based on the photometric data we have, we conclude that the dominant pulsation mode is indeed the radial first overtone.

In 9 stars we see a signal close to the primary frequency. Those stars are marked with ‘a’ in the remarks column, regardless of whether the signal is resolved or not. These stars were investigated for the Blazhko effect using combined OGLE-III and OGLE-IV data (see next Section). Typically irregular phase changes were detected. In one star, marked with ‘b’, we found harmonic of the additional mode. In one star, marked with ‘c’, signal close to additional frequency is seen (see next Section). In all stars additional signal is stationary.

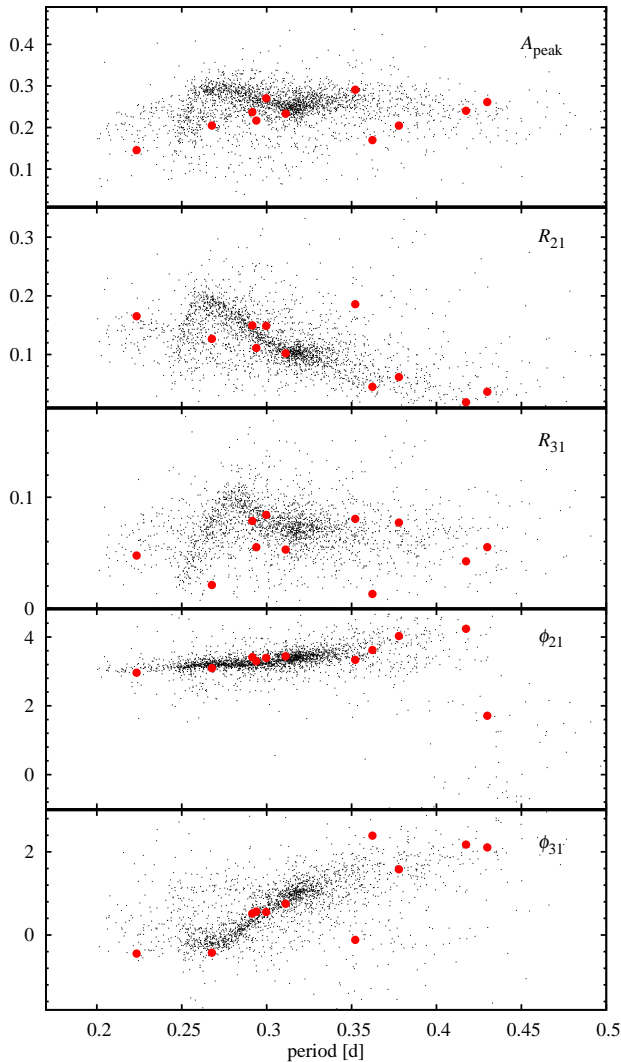
4 REMARKS ON INDIVIDUAL STARS

OGLE-BLG-RRLYR-05080. Part of the data in the first

Table 1. Stars with additional frequency. Subsequent columns contain periods of the first overtone and of additional signal, their ratio, amplitude of the first overtone and amplitude ratio. Two last columns contain form of the combination frequencies (if detected) and remarks.

star	P_{1O} (d)	P_x (d)	P_{1O}/P_x	A_{1O} (mag)	A_x/A_{1O}	combination freq.	remarks
OGLE-BLG-RRLYR-04994	0.3622954(3)	0.52797(1)	0.68619	0.0799(4)	0.048		a
OGLE-BLG-RRLYR-05080	0.2996982(1)	0.436810(5)	0.68611	0.1353(4)	0.048	$\nu_{1O} + \nu_x$	
OGLE-BLG-RRLYR-06970	0.42988998(7)	0.626497(9)	0.68618	0.1272(1)	0.012	$\nu_{1O} + \nu_x$	a
OGLE-BLG-RRLYR-07127	0.3778854(3)	0.55057(1)	0.68635	0.1009(5)	0.050		a
OGLE-BLG-RRLYR-07653	0.31118879(6)	0.454151(6)	0.68521	0.1166(2)	0.025		a
OGLE-BLG-RRLYR-08748	0.29153824(7)	0.424892(3)	0.68615	0.1185(3)	0.039		a,b
OGLE-BLG-RRLYR-09146	0.35215799(3)	0.5124233(5)	0.68724	0.1474(1)	0.028	$\nu_{1O} + \nu_x, 2\nu_{1O} + \nu_x$	c
OGLE-BLG-RRLYR-09217	0.29391346(2)	0.428719(1)	0.68556	0.1083(2)	0.026	$\nu_{1O} + \nu_x$	a
OGLE-BLG-RRLYR-09426	0.22339120(4)	0.325069(6)	0.68721	0.0724(2)	0.016	$\nu_{1O} + \nu_x$	a
OGLE-BLG-RRLYR-10100	0.4173796(2)	0.609497(8)	0.68479	0.1164(4)	0.060	$\nu_{1O} + \nu_x$	a
OGLE-BLG-RRLYR-32196	0.2677486(1)	0.390699(7)	0.68531	0.1008(4)	0.039		a
KIC9453114	0.3660809	0.5330831	0.68672	0.20664	0.004	$\nu_x - \nu_{1O}, \nu_x - 2\nu_{1O}$	

a – additional signal close to ν_{1O} ; b – harmonic of ν_x ; c – additional signal close to ν_x

**Figure 4.** Fourier decomposition parameters for RRc Galactic bulge stars (OGLE-III). Red points correspond to stars with the additional frequency. Rest of the RRc stars are marked with black dots.

season of observations is vertically shifted. We removed these data and analysed the rest.

OGLE-BLG-RRLYR-07653. After prewhitening the spectrum with a frequency of the first overtone and its harmonics, we still detect residual, unresolved signal at ν_{1O} . Time dependent analysis shows that amplitude and phase of the first overtone change with similar periodicity. We incorporate the OGLE-III data in the analysis to increase the frequency resolution. Length of the merged OGLE-III and OGLE-IV data is ≈ 6042 d, which allows to detect modulation period as long as 3020 d. Analysis of the combined data shows clear triplets at ν_{1O} and its harmonics, which we interpret as Blazhko effect. Period of the Blazhko modulation is 1698 ± 4 d. Additional frequency, at $\approx 0.68\nu_{1O}$, is visible both in OGLE-IV and in combined data.

OGLE-BLG-RRLYR-09146. The additional low frequency signal, ν_x , reported in Tab. 1 forms two linear combinations with ν_{1O} with $S/N > 4$ each. Yet another signal (ν_y) is visible on the higher frequency side of ν_x , at separation $\nu_y - \nu_x \approx 0.106 \text{ d}^{-1}$. Period ratio of this third frequency with the first overtone is 0.7245, too low to consider the additional signal as corresponding to radial fundamental mode. No combinations of ν_{1O} and ν_y are visible in the spectrum.

OGLE-BLG-RRLYR-32196. After prewhitening the data with ν_{1O} and its harmonics, additional close peaks (doublets) on the lower frequency side of ν_{1O} and $2\nu_{1O}$ are visible. These peaks may correspond to the Blazhko effect with incomplete triplets (and modulation period of 8.4 days) or to a non-radial mode. No OGLE-III data is available for this star.

5 SUMMARY AND CONCLUSIONS

We have discovered a new group of double-periodic RR Lyrae stars with the dominant pulsation in the radial first overtone. Additional period is longer than the first overtone period and longer than the expected period of the unseen fundamental mode. Period ratios between the first overtone and additional period tightly cluster around 0.686, independently of the first overtone period (which covers a

broad range from ≈ 0.22 to ≈ 0.42 d). Amplitude of the additional periodicity is in the mmag range and is only a small fraction of the first overtone amplitude (up to 6 per cent). The group counts 12 stars, 11 identified in the OGLE-IV Galactic bulge photometry and one in *Kepler* observations. In two stars we detect the Blazhko modulation. Irregular phase variation, which is typical for RRc stars, is detected in most cases. The signal corresponding to additional periodicity is always stationary.

Excitation of an additional oscillation mode in these RRc stars seems the only possible interpretation of the additional signal. The frequency, though lower than ν_F , is still well above the Keplerian frequency and this rules out all interpretations in terms of spots or a companion. We note that instability may extend below the frequency of the fundamental mode, as is the case for some dipole modes plotted in fig. 2 of Dziembowski & Cassisi (1999). These modes are of mixed character. To check whether instability extends sufficiently below ν_F , so it matches the $\approx 0.68\nu_{10}$ modes, a careful analysis of a grid of full evolutionary models is required, which is ongoing (Dziembowski, in prep.). Still, the expected driving rates (Van Hoolst, Dziembowski & Kawaler 1998; Dziembowski & Cassisi 1999) are orders of magnitude lower than driving rates for the radial modes. The driving rates are not a good predictors of the pulsation amplitude or of the form of the finite amplitude pulsation (mode selection, e.g. Smolec 2014). Still, the orders of magnitude lower driving rates than in apparently not excited fundamental mode are worrying.

We anticipate a further detections of stars with additional low frequency periodicity during the ongoing K2 mission. The precise space photometry may shed more light on the nature of these mysterious RRc pulsators.

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